Characterization of High-Burnup PWR and BWR Rods

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Limerick and H. B. Robinson Rod Characterization

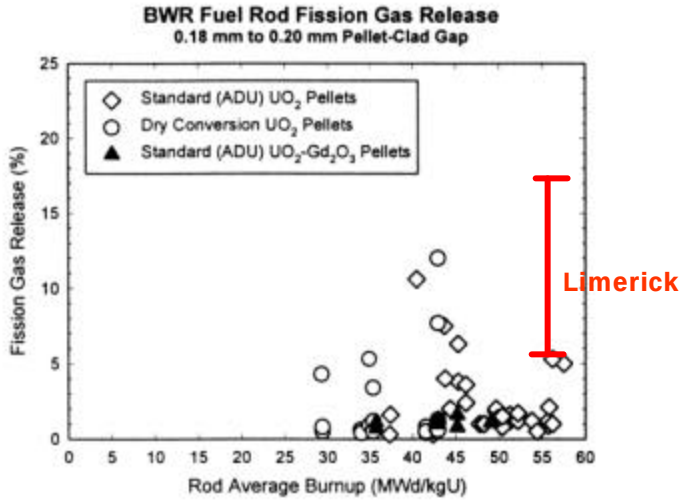
- **Objective: Generating baseline data for the LOCA, dry-cask storage, and YMP-related work**
  - **Data also useful for burnup extension deliberations**
- **PWR Rods - H. B. Robinson**
  - **15x15, 5-7-cycle, 67 GWd/MTU**
  - **Zry-4, 1.42% Sn, CW/SR**
  - **Pool-side data: 110 µm oxide, 2.4% fission-gas release, 1.1% rod growth, 1.1% creepdown (all peak values)**
- **BWR Rods - Limerick**
  - **9x9, 3-cycle, 56 GWd/MTU**
  - **Lined Zry-2, recrystallized-annealed**
  - **Pool-side data: modest corrosion and creepdown**

Limerick and H. B. Robinson Rod Characterization

- **Scope of Characterization**
  - **Fission-gas release**
  - **Axial gamma scanning**
  - **Optical metallography**
    - **Fuel, fuel/cladding interface, cladding corrosion, hydrides, and microhardness**
  - **Cladding hydrogen and oxygen analyses**
  - **Microprobe analysis**
    - **U, Pu, and fission product distribution**
  - **Isotopic analysis**

Limerick and H. B. Robinson Rod Characterization

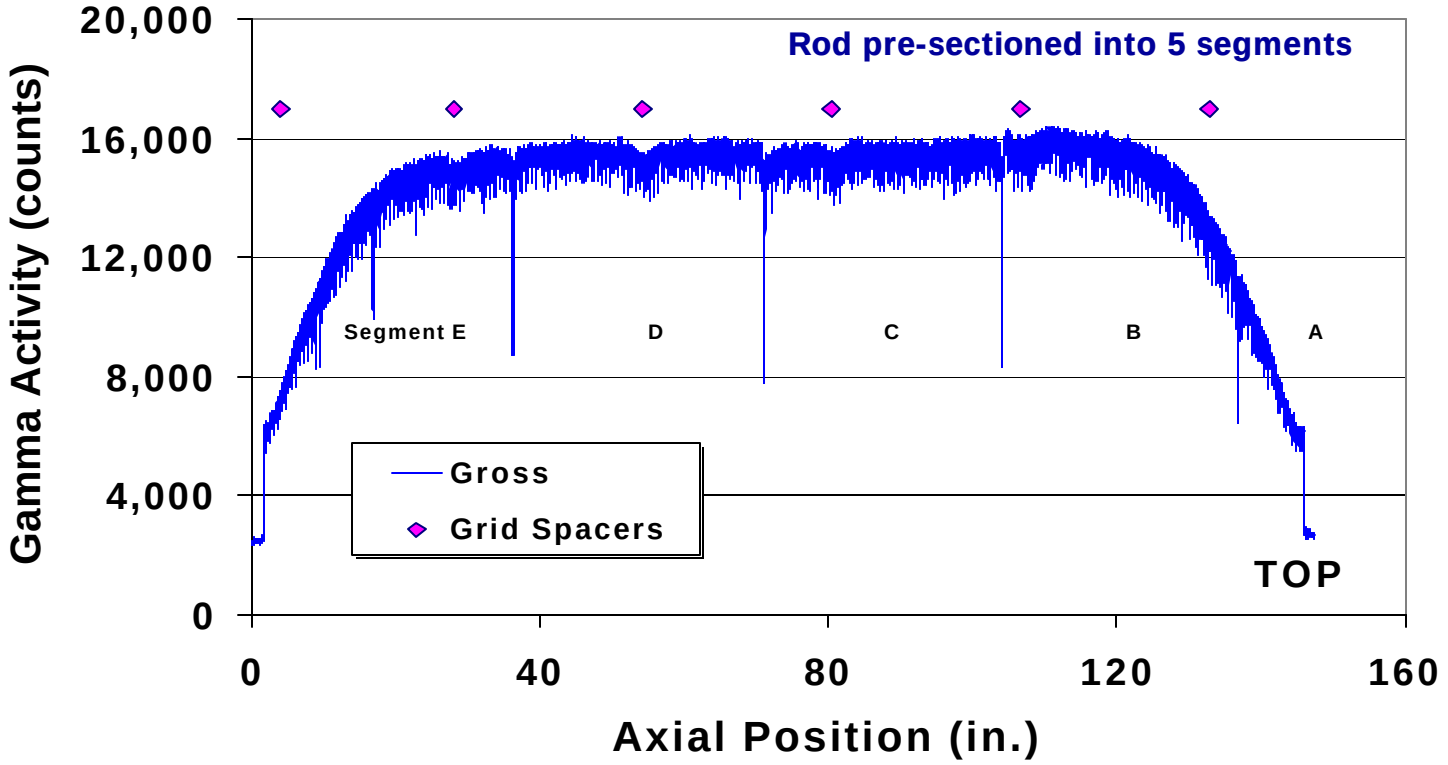
- **Fission Gas Release**
  - **H. B. Robinson rods: 1.4 – 2.5%**
    - **Probably due to the relatively low linear power: ~ 8 kW/ft BOL decreasing to 3-4 kW/ft EOL**
  - **Limerick rods: 5 – 17%**
    - **Relatively high release attributable possibly to fuel microstructure**



From Van Swan et al. '97 Portland

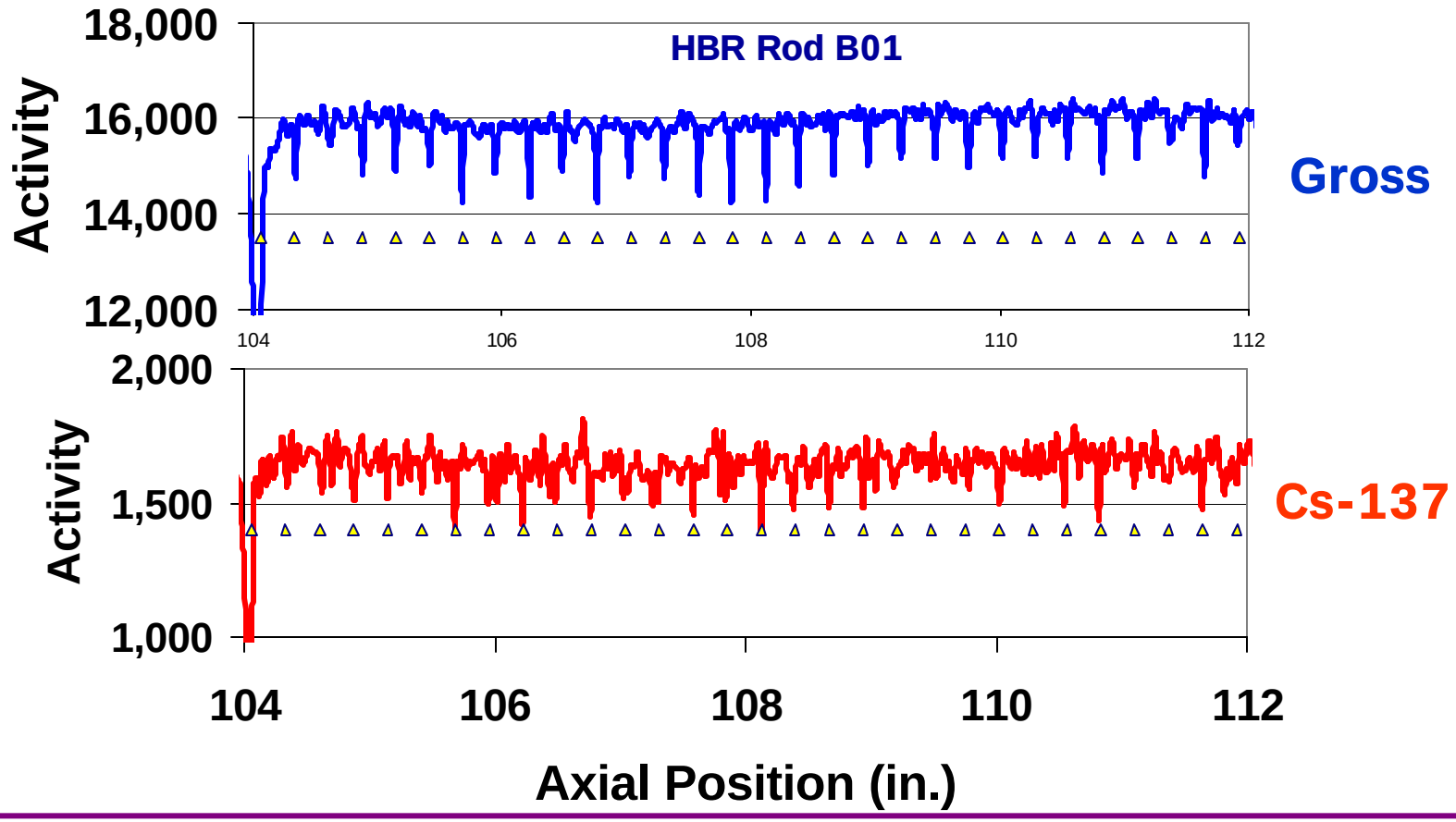
H. B. Robinson Rod Characterization

- **Axial Gamma Profile (HBR Rod B01)**
  - **Distribution as-expected.**
  - **Slight dips at grid spacers.**



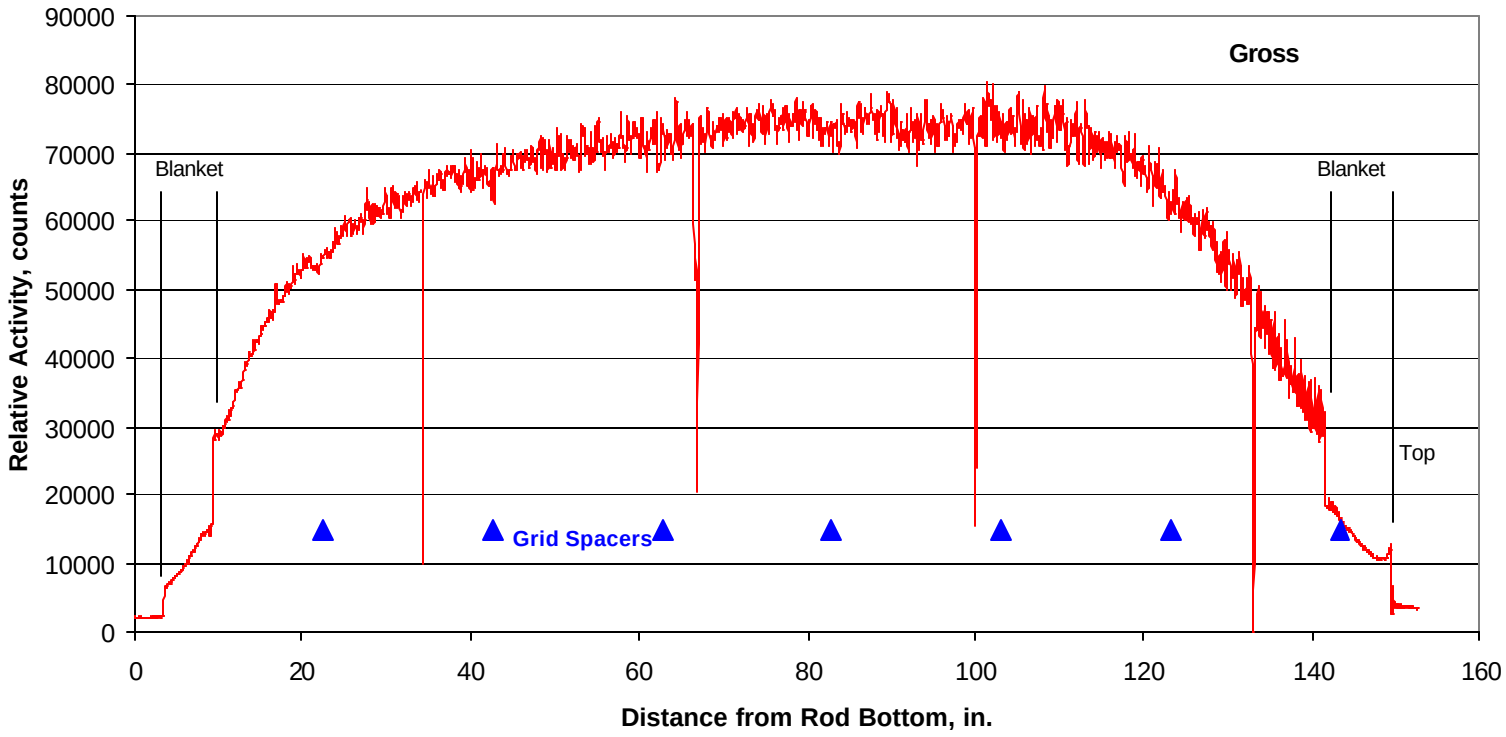
H. B. Robinson Rod Characterization

- **Some Cs mobility. No significant fission product migration.**



Limerick Rod Characterization

- **Axial Gamma Profile (Limerick Rod F9)**
  - **No unusual features.**

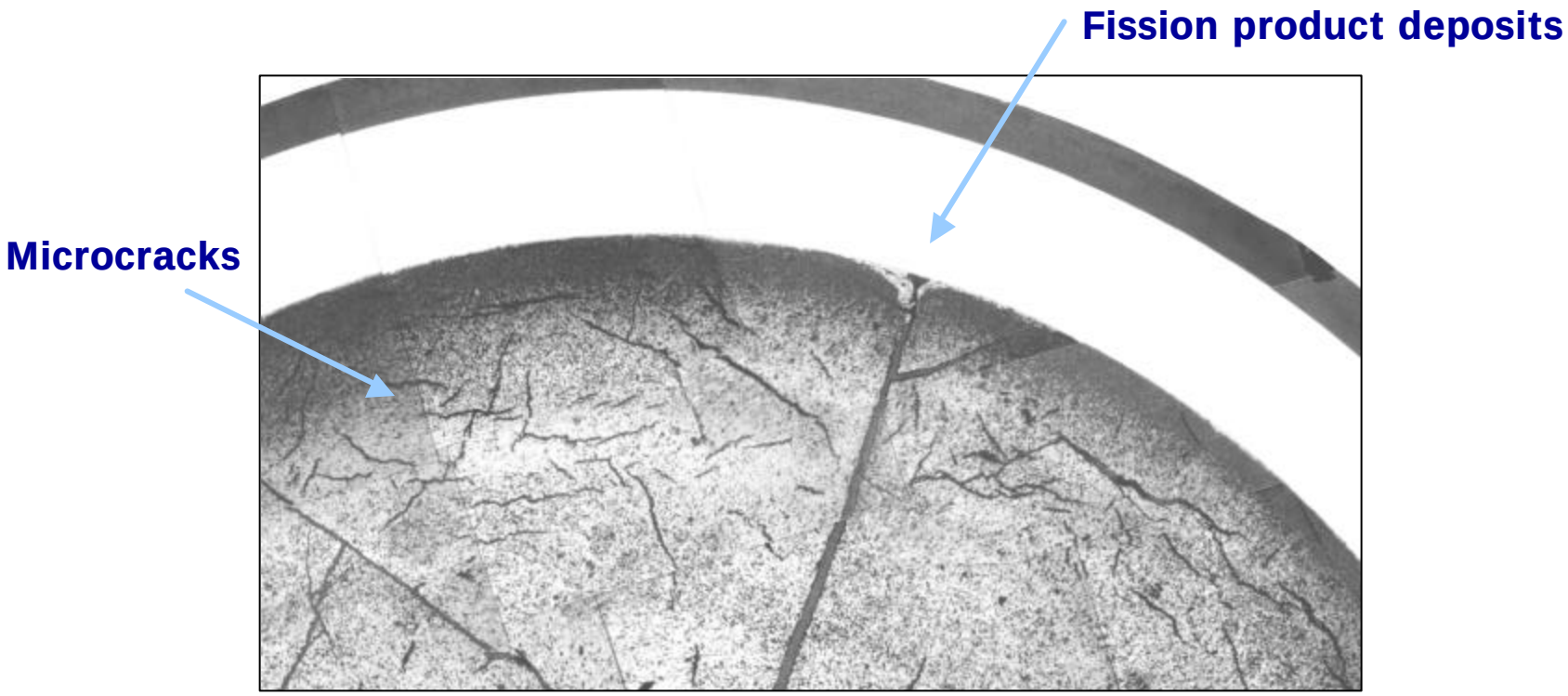


Limerick Rod Characterization

- **Limerick Rod F9, at 31 in. above midplane**
  - **Fuel cracking: normal**
  - **Discontinuous and off-centered "temperature markers" in fuel**
    - **Edge rod**
  - **Porous fuel "rim"**
  - **Numerous Fuel microcracks in gaseous outer region**
  - **Tight fuel/cladding bond**
    - **Fission product deposits in fuel/cladding gap and at tips of major fuel cracks**

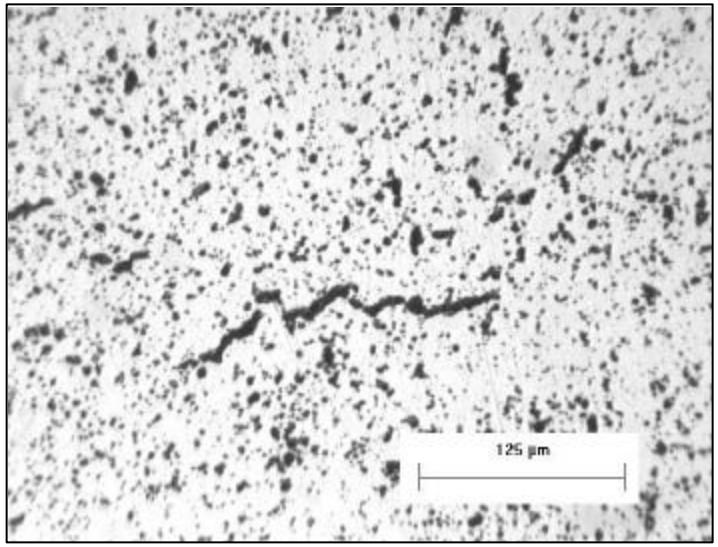
Limerick Rod Characterization

- **Fuel microcracks in and near the rim**
  - **Formed on grain boundaries weakened by fission-gas bubbles**
  - **May enhance gas connectivity and fuel relocation in LOCA**

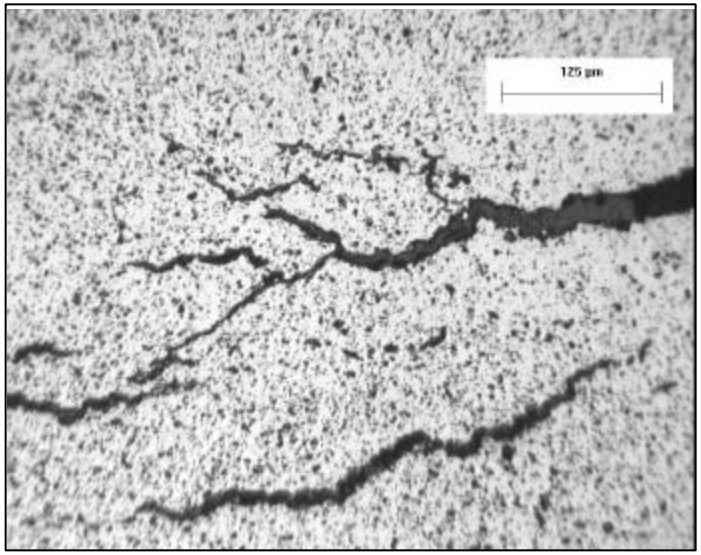


Limerick Rod Characterization

- **Fuel microcracks**



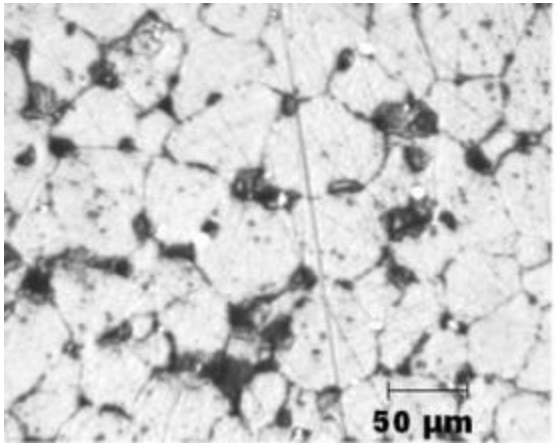
Incipient



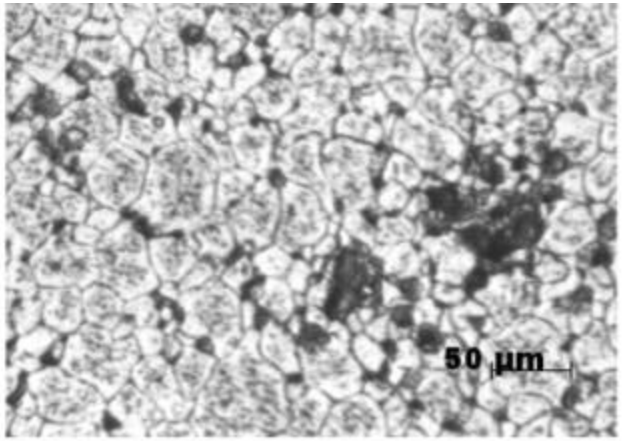
More developed

Limerick Rod Characterization

- **Fuel Structure**
  - **Center – apparent grain growth, large f.g. bubble on GB**
  - **Midradius – numerous fine f.g. bubbles in grains**
  - **Rim – small grains, numerous f.g. bubbles in grains and on GB**



Center

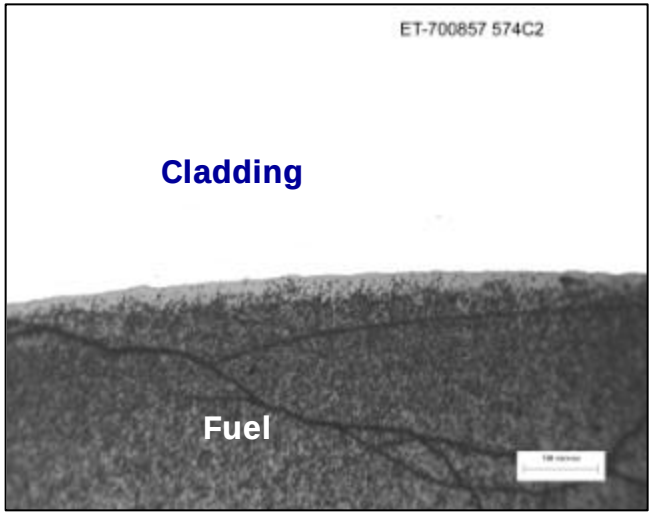


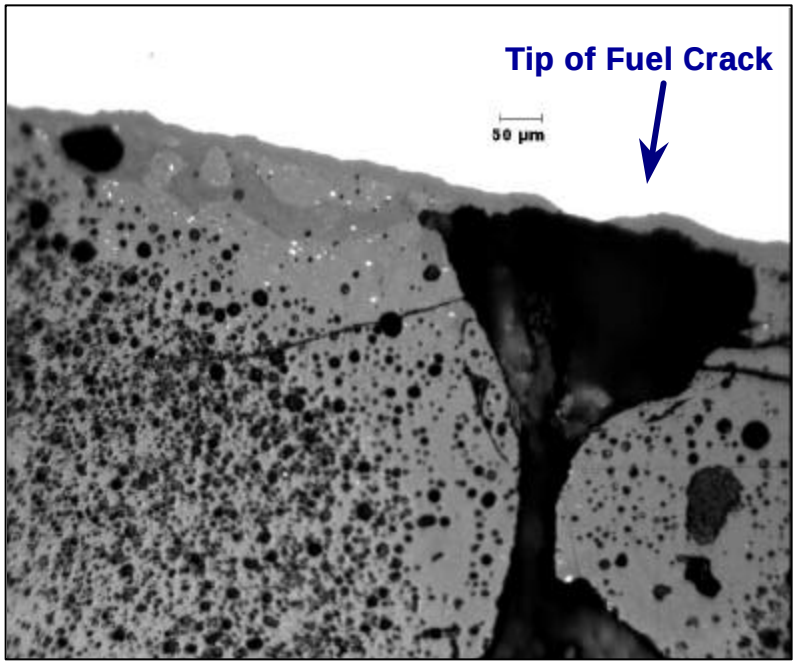
Midradius

Rim

Limerick Rod Characterization

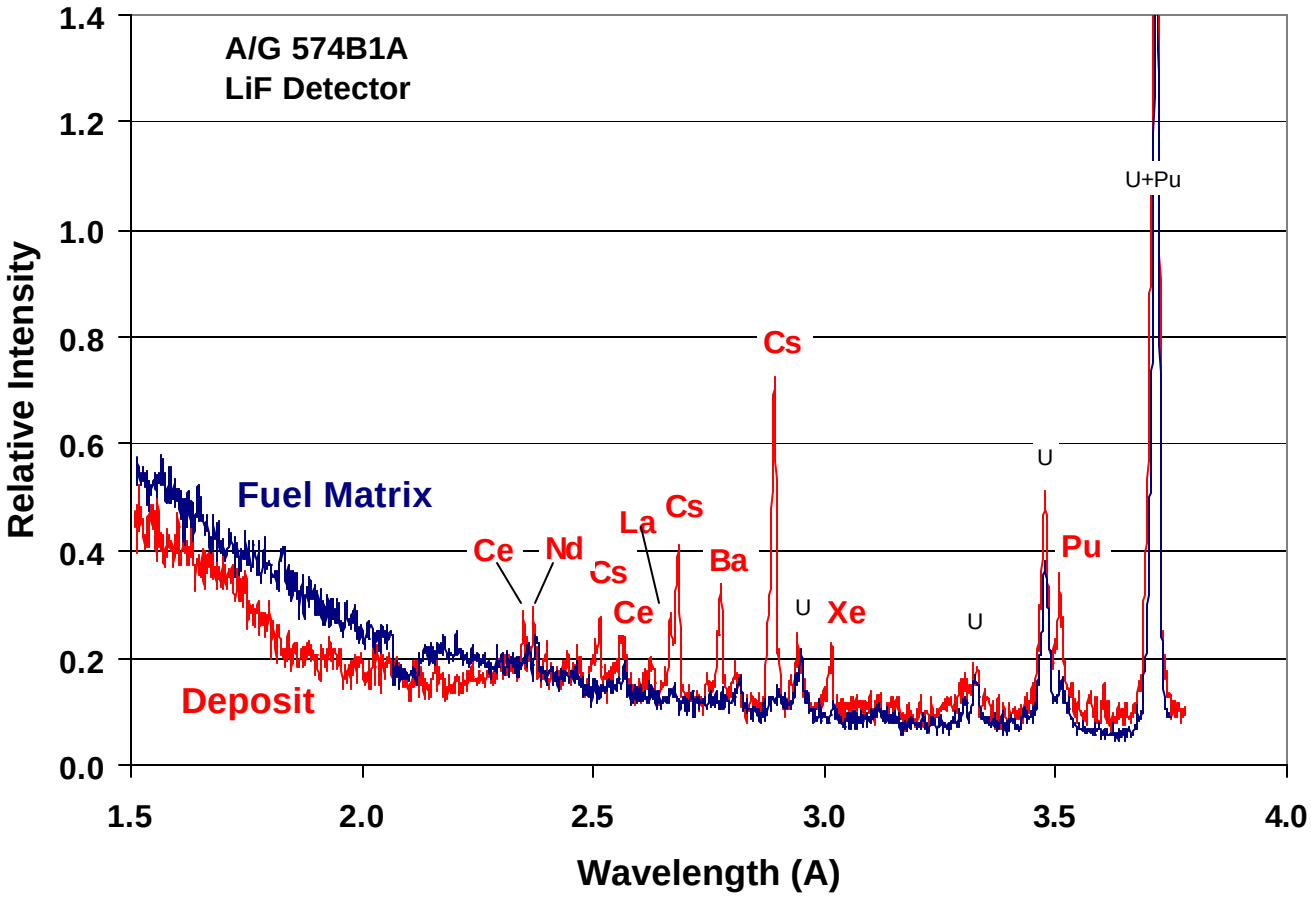
- **Fuel/Cladding Interface**
  - **Tight fuel/cladding bond**
  - **Fission-product deposits in the gap and at the tips of fuel cracks**
  - **No significant cladding interaction, however.**





Limerick Rod Characterization

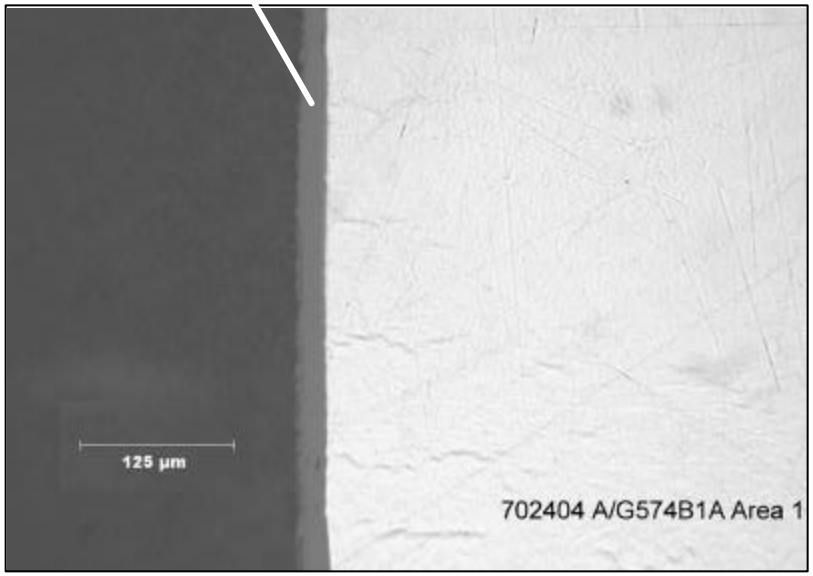
Microprobe: Deposit at fuel crack tip contains fission products and Pu



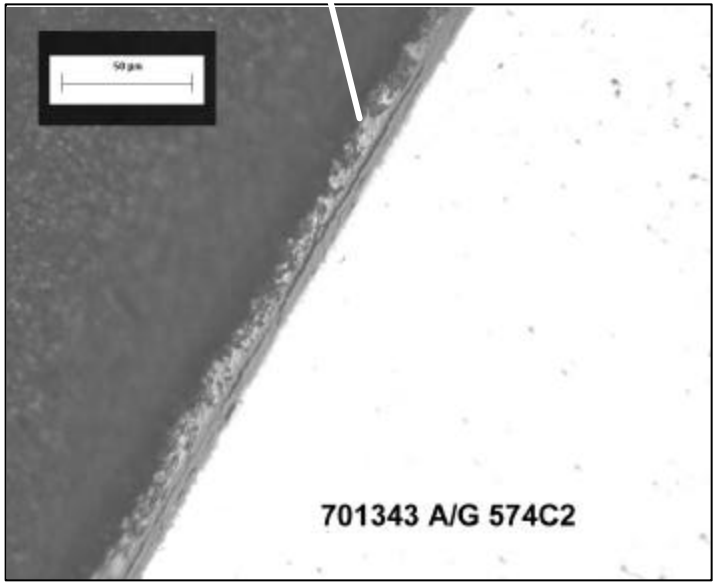
Limerick Rod Characterization

- **Cladding Surface Layers**
  - **Oxide thin and variable. Max. thick. »25 µm; average »10 µm.**
  - **Tenacious crud (»5 - 10 µm) occurs where oxide is thin. Crud contains Zn and (Fe, Ni, Co, Mn), likely a zinc ferrite.**

Oxide

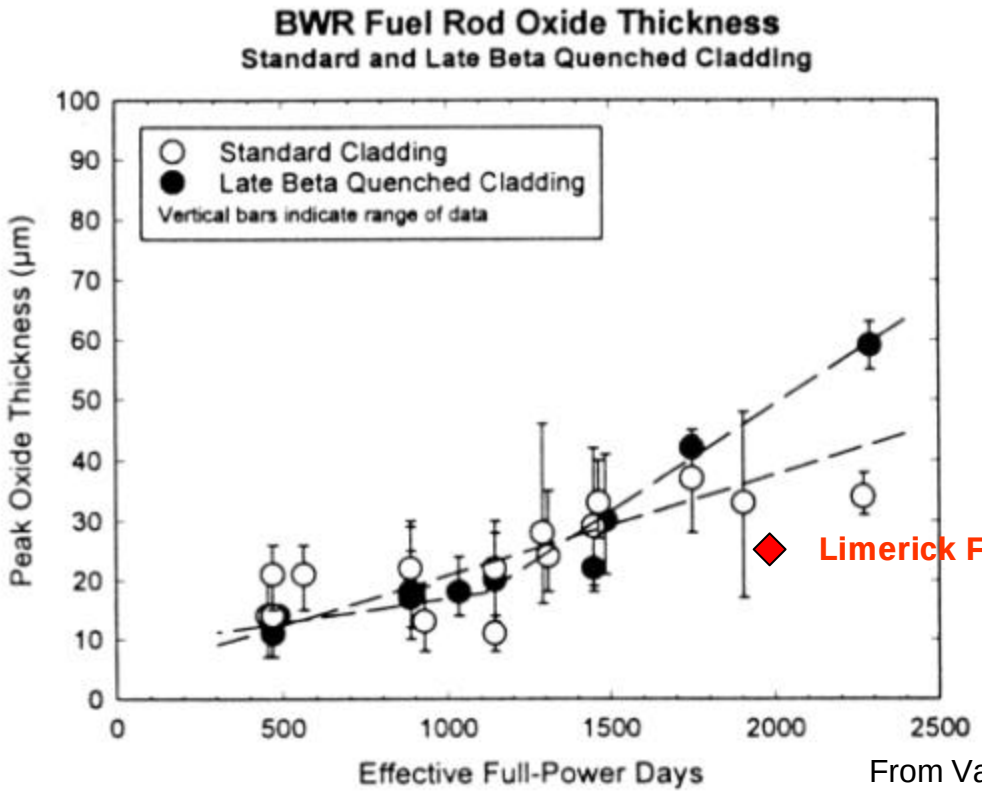


Crud over oxide



Limerick Rod Characterization

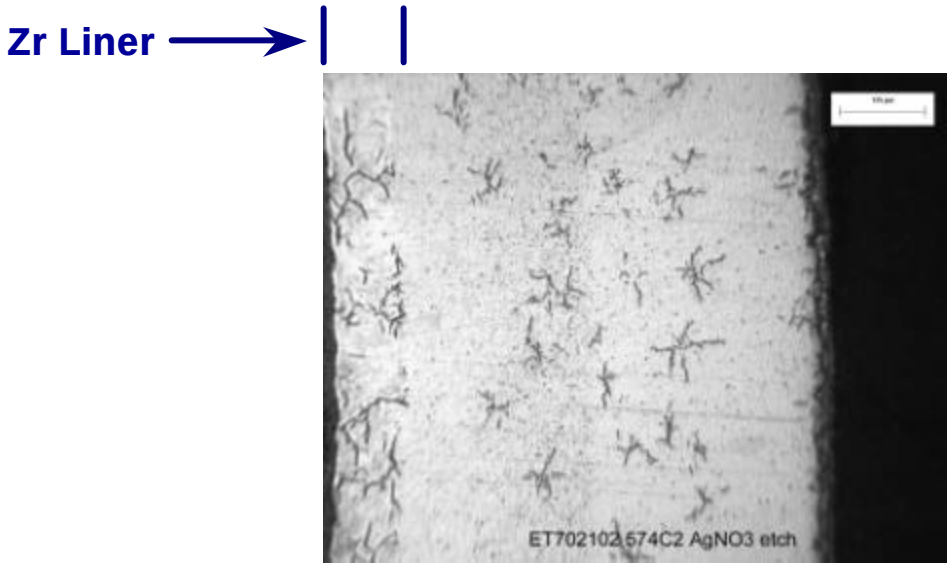
- **Corrosion in Limerick - modest**



From Van Swan et al. '97 Portland

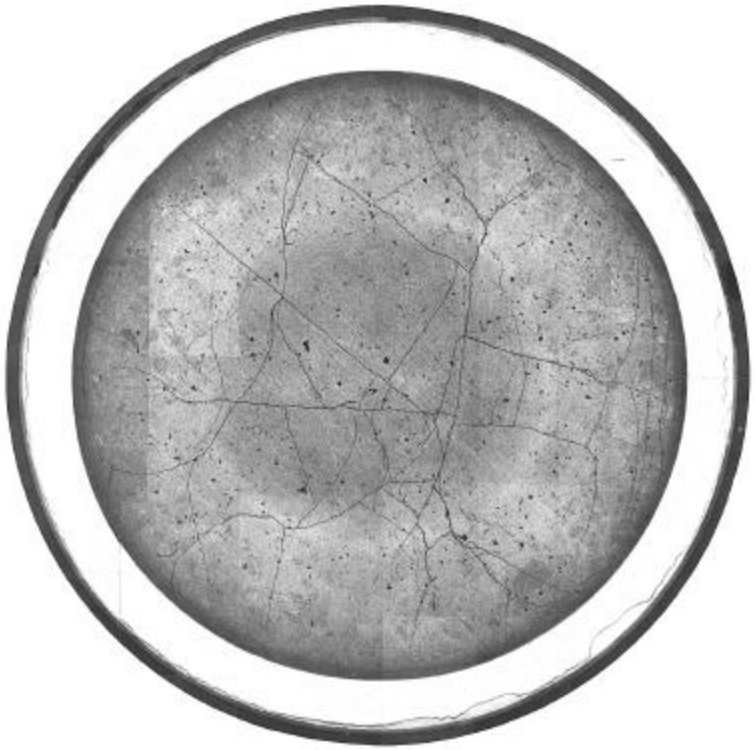
Limerick Rod Characterization

- **Hydrides in Limerick F9 Cladding**
  - **H preferentially precipitated in the low-O Zr liner.**
  - **Hydride platelets are small, a few near the outer surface.**
  - **Measured H content is low, »70 wppm.**

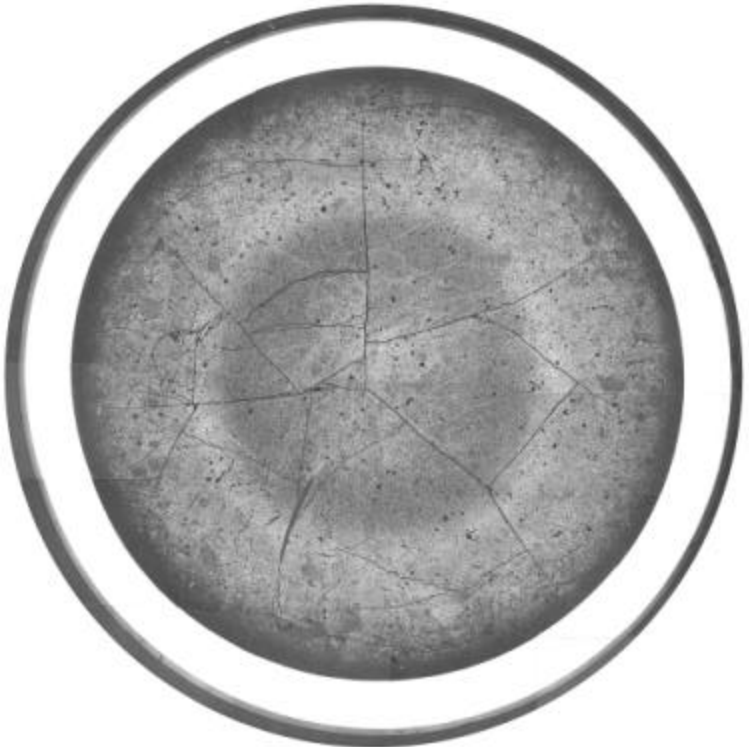


H. B. Robinson Rod Characterization

- **Transverse cross sections of HBR Rod A02**



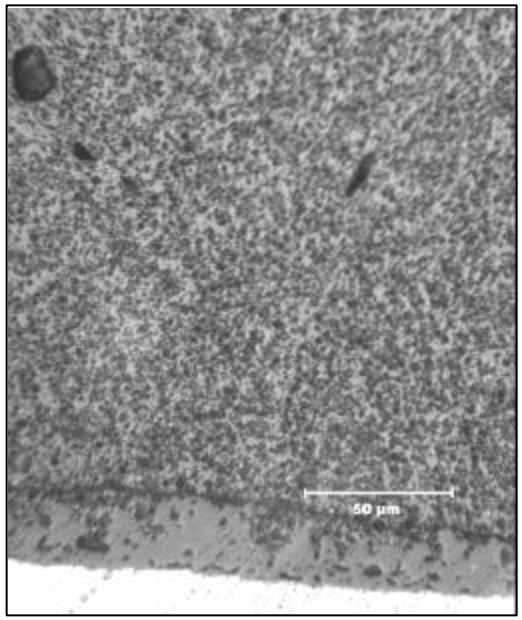
Midplane



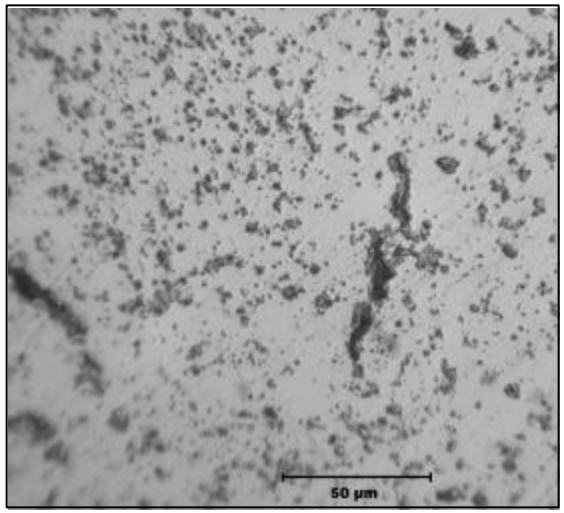
27 in. above midplane

H. B. Robinson Rod Characterization

- **Fuel "Rim" and microcracks**



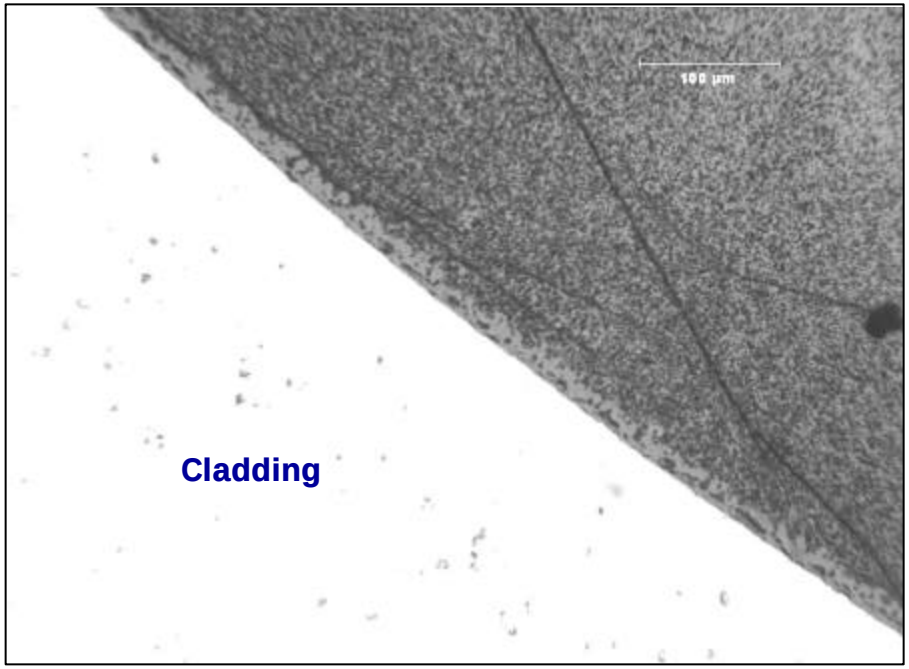
"rim"



mid-radius (microcracks)

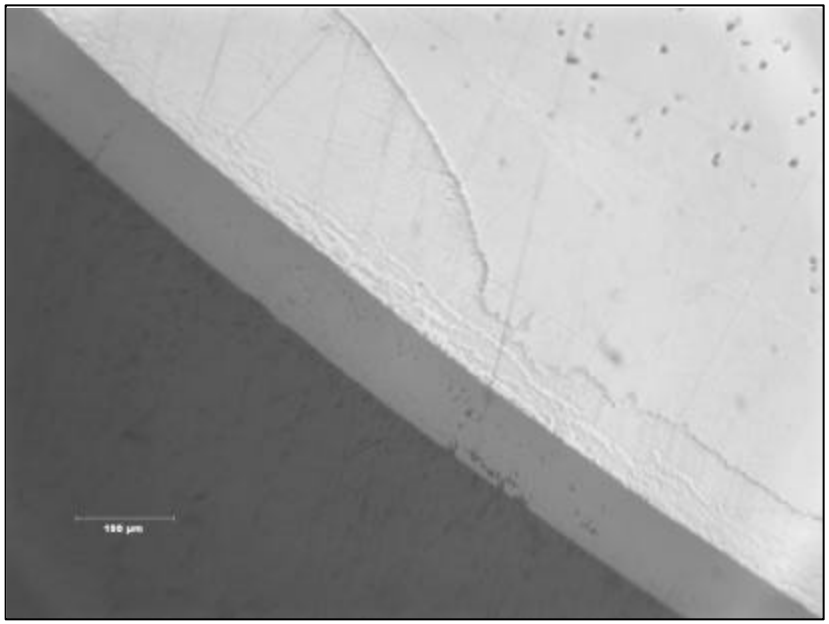
H. B. Robinson Rod Characterization

- **Fuel/cladding Interface**
  - **No significant fuel/cladding chemical interaction**
  - **Tight fuel/cladding bond**

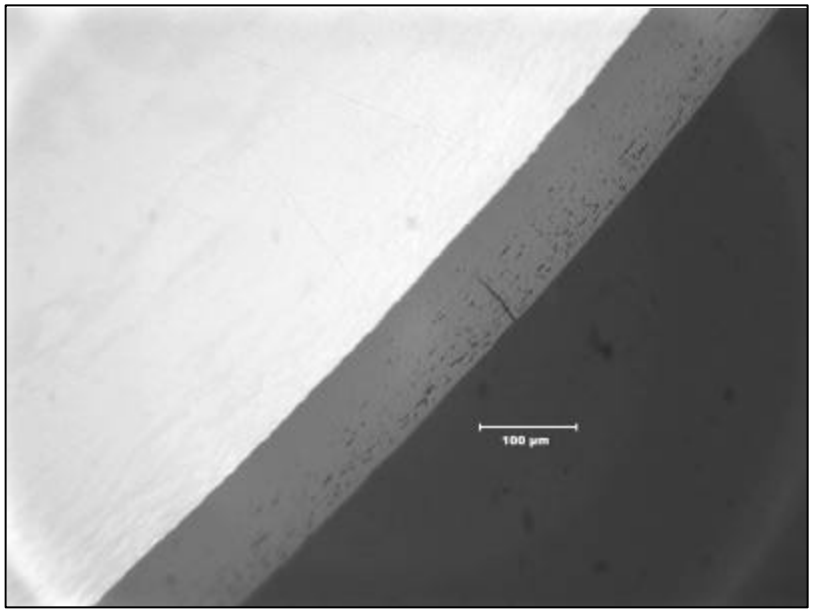


H. B. Robinson Rod Characterization

- **OD Oxide Layer – thickness corroborating pool-side NDE data** **(“95 µm in Span 4,” EPRI 1001558)**



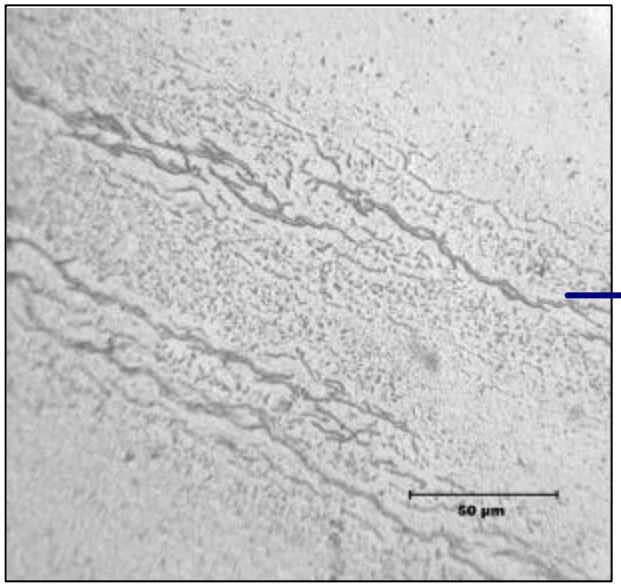
Midplane
(70 µm circum. avg.)



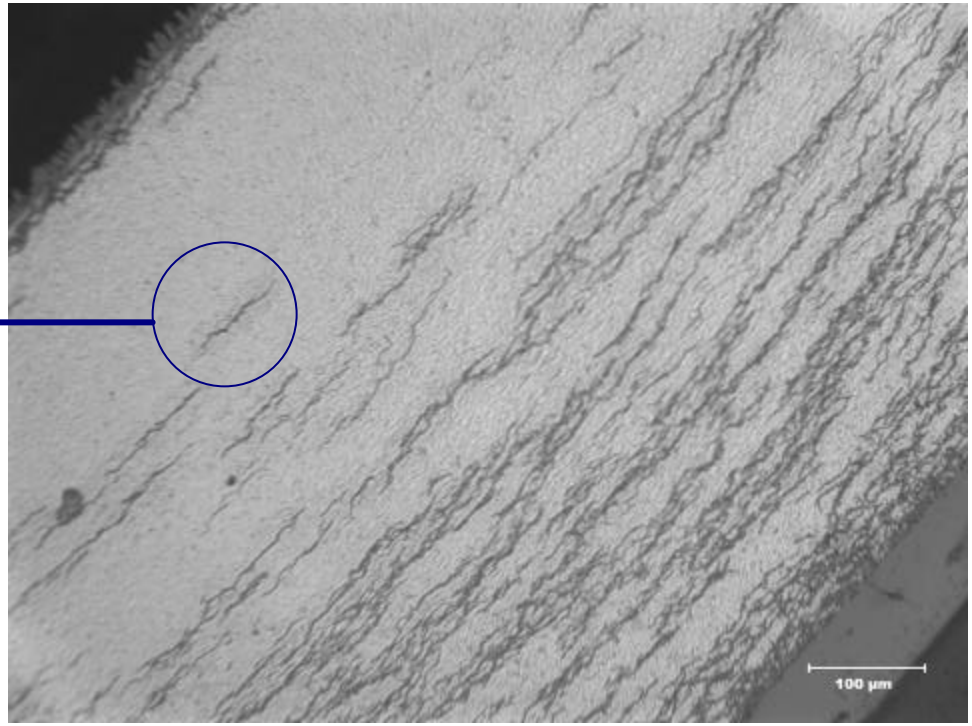
27 in. above midplane
(98 µm circum. avg.)

H. B. Robinson Rod Characterization

- **Typical Hydride Morphology (axial midplane)**

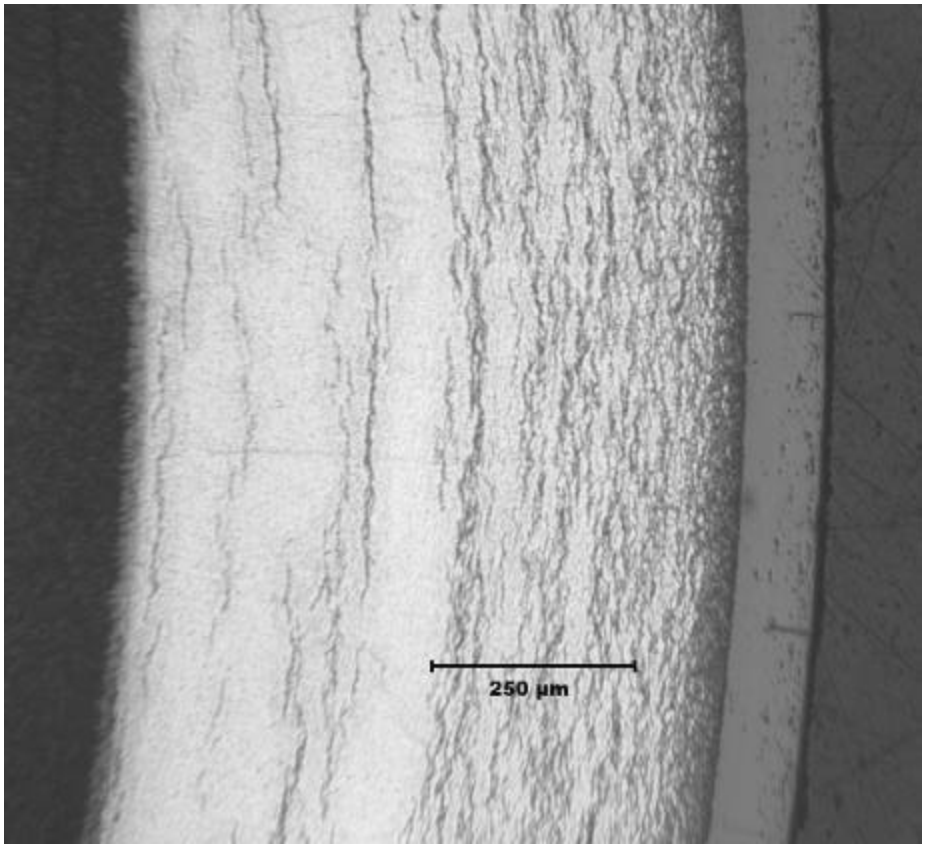


Fine precipitates around platelets



H. B. Robinson Rod Characterization

- **Typical Hydride Morphology (27 in. above)**



H. B. Robinson Rod Characterization

- **Measured Cladding Hydrogen Contents**
  - **Uptake ratios appear normal**

	Axial Midplane	27 in. above Midplane
Oxide Thick. (μm)	70	98
H Content (wppm)	579±63	752±87
% H Uptake*	21	23

*** Assuming a Pilling-Bedworth ratio of 1.75**

Limerick and H. B. Robinson Rod Characterization

- **Summary and Conclusions – Limerick**
  - **Oxide and crud layers both thin**
  - **H content in cladding low (˜ 70 wppm), commensurate with the thin oxide layer**
  - **Fission-gas release relatively high, possibly attributable to fuel microcracking**
  - **Fuel/cladding gap filled with fission products. No significant cladding interaction, however.**
  - **Sound overall condition in spite of the high burnup.**

Limerick and H. B. Robinson Rod Characterization

- **Summary and Conclusions – H. B. Robinson**
  - **Low fission-gas release**
  - **Tight fuel/cladding bond. No significant fuel/cladding interaction**
  - **Max. OD oxide thickness ~ 100 µm**
  - **Cladding hydrogen content of ~ 750 wppm at 27 in. above midplane agrees with oxide thickness**
  - **Effects of hydrogen on cladding behavior being evaluated in**
    - **Integral LOCA criteria tests**
    - **Cladding tensile tests**
    - **Cladding thermal creep tests.**